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ATMOSPHERIC ABSORPTION OF LOW FREQUENCY SOUND AT HIGH PRESSURES--ETC(U)

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UNCLASSIFIED WR-76-13 ARO-12916.2-E NL

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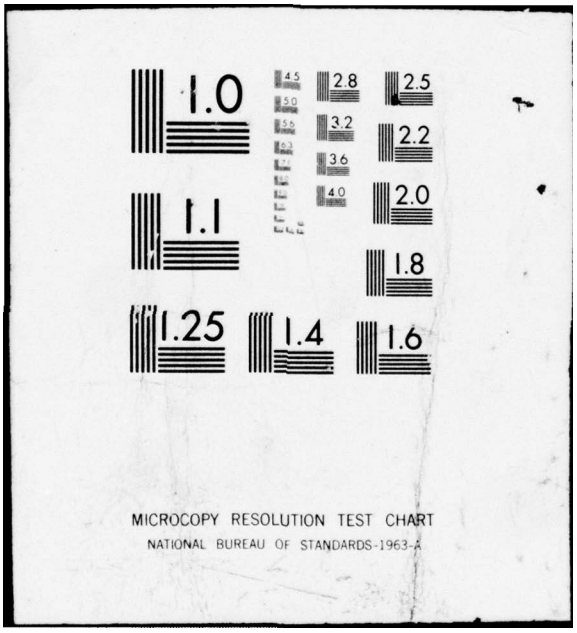
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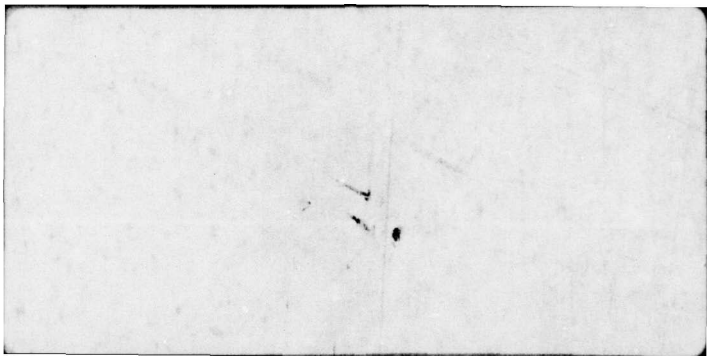

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WYLE RESEARCH REPORT

WR 76-13

ATMOSPHERIC ABSORPTION OF LOW FREQUENCY SOUND AT HIGH PRESSURES

FINAL REPORT

Prepared For:

U.S. Army Research Office
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North Carolina

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August 1976

REPORT

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER

4. TITLE *(and Subtitle)*
Atmospheric Absorption of Low Frequency Sound at High Pressures,

5. TYPE OF REPORT & PERIOD COVERED
Final Report,
23 Jun[redacted]75 - 22 Jun[redacted]976,

6. PERFORMING ORG. REPORT NUMBER
WR-76-13

7. AUTHOR(s)
M.C. Lee
L.C. Sutherland

8. CONTRACT OR GRANT NUMBER(s)
DAHC04-75-C-0027 NEW

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Wyle Laboratories
~~Wyle Research~~
128 Maryland Street
El Segundo, California 90245

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
12 35 p.

11. CONTROLLING OFFICE NAME AND ADDRESS
U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, NC 27709

12. REPORT DATE
Aug[redacted]976

13. NUMBER OF PAGES
33

14. MONITORING AGENCY NAME & ADDRESS *(If different from Controlling Office)*
18 ARO
19 12916.2-E

15. SECURITY CLASS. *(of this report)*
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
NA

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

NA

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*
Propagation
Atmosphere
Sound Absorption

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
Results of a limited experimental study of atmospheric absorption in moist air at low frequencies are reported. The measurements were carried out in a resonance absorption tube at ratios of frequency to pressure of 4.6 to 403 Hz/atm. This extends the f/P range of laboratory measurements of absorption in air well below limits of previously published data in air of about 140 Hz/atm. The experimental apparatus was calibrated, using argon, over the same f/P range. The measured and predicted absorption in air and in argon generally agreed with existing theoretical models, although substantial deviations remain to be explained.

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ABSTRACT

Results of a limited experimental study of atmospheric absorption in moist air at low frequencies are reported. The measurements were carried out in a resonance absorption tube at ratios of frequency to pressure of 4.6 to 403 Hz/atm. This extends the f/P range of laboratory measurements of absorption in air well below limits of previously published data in air of about 140 Hz/atm. The experimental apparatus was calibrated, using argon, over the same f/P range. The measured and predicted absorption in air and in argon generally agreed with existing theoretical models, although substantial deviations remain to be explained.

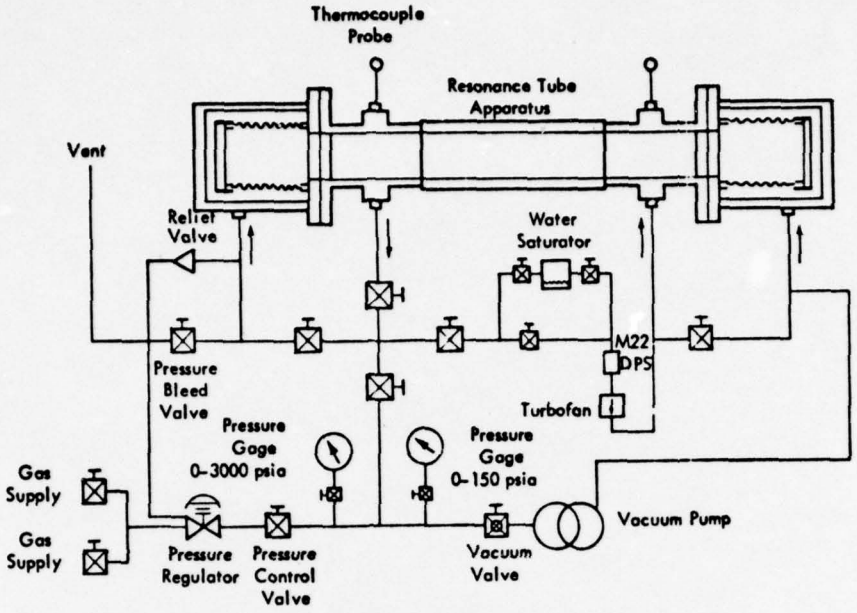
1. INTRODUCTION

This research program has been carried out to investigate the absorption in moist air and its constituent gases at low frequencies with the use of a resonance tube apparatus. The apparatus is shown schematically in Figure 1. It consists primarily of a 1 meter right circular cylinder capable of containing gases to 100 atm and associated gas-handling and electroacoustic instrumentation. This enables measurements to be made of acoustic (volume) absorption of gases by a resonance decay method. The apparatus and test procedure have been described in detail in an earlier publication.[1] The design of the apparatus was based on a similar system used by Roessler[2] while the experimental techniques were patterned after the studies by Edmonds and Lamb[3] and Fritsche[4] and the pressure scaling concepts outlined in Appendix A.

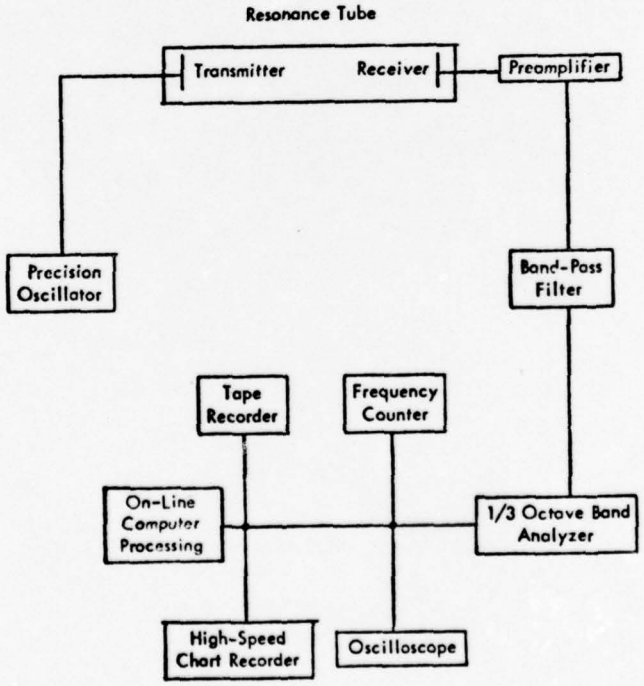
The initial study, using this apparatus, reported in Reference 1, indicated that the device performed as expected in that measured and predicted surface losses agreed within 1 or 2 percent. However, practical difficulties in repeated operation of the apparatus, as initially constructed, required further modifications before additional tests could be made. While all of the initial objectives of the program were not achieved due to the difficulties encountered resulting from these unexpected changes in the apparatus, unique data were obtained on volume absorption in relatively dry air at low frequencies (4.6 to 403 Hz per atm) with the modified apparatus. These results, briefly summarized in the remainder of this report, are applicable to studies of sound propagation from low frequency sources such as gunfire, rockets, or various natural phenomena (i.e., thunderstorms).

2. RESULTS

During the initial phase of the current reporting period (July 1975 to June 1976), the resonance apparatus was moved into a remotely-located mobile laboratory to minimize hazards with high-pressure operation and to achieve a low electrical noise background. In addition, three major modifications were made to improve the mechanical operation of the experimental apparatus and increase the quality of the measurements.



a) Gas Handling System



b) Instrumentation

Figure 1. Schematic Diagram of Resonance Tube Apparatus

First, the manual jackscrew-operated sealing mechanism for the high-pressure test chamber[1] was replaced by a hydraulically-operated system. A preset hydraulic pressure could be applied to the sealing piston to ensure a positive seal. Secondly, the tubing size of the humidity circulating system was changed from 1/4 inch (.635 cm) to 1/2 inch (1.27 cm). The flow rate of the gas was therefore increased by approximately four times. This higher flow rate shorted the length of time required to stabilize the humidity content throughout the system and insured a uniform humidity content throughout. Finally, for the convenience of gaining access to the tube interior for any purpose such as replacing the acoustic transducers, a built-in dolly assembly was installed beneath the center test chamber enabling a quick disengagement of the heavy test chamber ($\sim$ 600 lbs) from the rest of the apparatus. Except for the above modifications, the apparatus, instrumentation, and measurement techniques applied were essentially the same as previously reported.[1]

The resonance tube was calibrated with a research grade dry argon gas for four different pressures (1, 9.5, 50.66, and 98.82 atm). The argon gas contained less than 20 parts per million of contaminants according to the supplier's certification. Data in research grade air were obtained under the conditions of frequency and pressure which were expected to yield maximum molecular absorption of oxygen. The air, prior to addition of moisture was a high purity research grade mixture obtained commercially and consisted of 20.95 percent oxygen, 79.02 percent nitrogen, and 0.03 percent carbon dioxide. The conditions employed for the eight tests conducted are summarized in the following table..

Data reduction consisted of measuring the total (surface plus volume) absorption losses in terms of the decay or reverberation time. The latter measurement was actually carried out by automatic linear curve fitting, applied with a minicomputer, to recorded samples of the decay time histories. This total absorption loss was then corrected for wall losses according to the procedures in References 2 to 4. The latter consist of:

- Thermal and viscous boundary layer losses at the cylindrical wall and end surfaces (vary directly as (frequency/pressure)$^{1/2}$ and as a function of viscosity).
- Direct mechanical radiation losses through the cylindrical wall (vary directly as pressure, independent of frequency).

Table 1

Experimental Conditions

Gas	Pressure (atm)	Humidity Percent Mole Ratio	Temperature (°K)	f/p Range (Hz/atm)
Argon	1.00	Dry	291.9	178 - 3724
	9.50	Dry	291.6	17.3 - 386
	50.7	Dry	294.3	3.28 - 73.2
	98.8	Dry	294.3	1.73 - 38.7
Air	9.84	1.31×10^{-2}	294.4	18.1 - 403
	35.7	3.94×10^{-3}	294.4	4.98 - 112
	50.0	2.48×10^{-3}	293.3	3.55 - 79.6
	78.5	1.69×10^{-3}	294.9	2.31 - 51.4

For the remaining (volume) loss, the classical absorption loss would normally be subtracted out using the current and well-validated theoretical model defined in Reference 5. However, for the experimental range of the tests in air in this study, classical loss amounted to less than 0.1 percent of the total volume loss and was therefore neglected since this is within the measurement accuracy. The measured volume loss was therefore attributed to molecular relaxation loss, primarily that of O_2 and N_2.[5, 6] Throughout this data reduction analysis, the theoretical (and experimentally-verified) variation in viscosity of the gases with pressure and temperature was used - thus accounting for real gas effects at high pressure.[7] A precise measure of the

speed of sound in the gas was also required for the analysis and this was evaluated by a self-consistent iteration process outlined in Reference 1 which inherently accounts for real gas and relaxation effects on the speed of sound.

The experimental results are presented in the form of the following computer printout package. This consists of the computer program for data reduction (written in TYMSHARE SUPERFORTRAN) (Table 2), and eight tables of computer printout for the data obtained (Tables 3-10). The first four tables contain the calibration of the tube in argon. The last four tables contain the data of the resonance tube conducted with moist air in the resonance tube. A glossary of the terminology used in each data table is given in Table 2a. For example, as defined in Table 2a, the columns labeled EALPPW in Tables 7 to 10 are experimentally measured values of volume attenuation ($\alpha\lambda$) in nepers per wavelength, and the columns labeled ALPPW contain the calculated values of $\alpha\lambda$ based on the procedures outlined in Reference 5.

The temperature of the system was determined with an accuracy of ±0.2°C. by direct measurement and by indirect calculation from the determination of the speed of sound. The pressure was measured by a precision Bourdon pressure gauge accurate to within ±2 percent. The humidity was measured with a dew point hygrometer with a range from -100°C to 60°C and an accuracy of ±2°C. The frequency of the test signal was determined to an accuracy of better than 0.1 percent by an electronic counter.

3. CONCLUSIONS

Results of a limited experimental study of atmospheric absorption in moist air at low frequencies are reported. The measurements were carried out in a resonance absorption tube at ratios of frequency to pressure of 4.6 to 403 Hz/atm. This extends the f/P range of laboratory measurements of absorption in air well below limits of previously published data in air of about 140 Hz/atm. The experimental apparatus was calibrated, using argon, over the same f/P range. The measured and predicted absorption in air and in argon generally agreed with existing theoretical models, although substantial deviations remain to be explained.

The average difference between measured wall losses in the tube and theoretical values for argon over all the data from 9.5 to 98.8 atm was -0.2 percent. However, the standard deviation was about ±12 percent, reflecting a systematic trend of increasing deviation between measured and predicted wall losses at high pressures and low frequencies, as shown in Figure 2. Whether this anomalous behavior is due to a systematic measurement error or an error in the theoretical model for wall losses, as defined in References 2, 3, and 4, is not clear.

The measured values of absorption in air assumed that the theoretical wall losses were correct. Based on this assumption, over 70 percent of the measured data fall within ±15 percent of the predicted values for absorption in moist air. The data, at 78.5 atm, covering the lowest range of f/P, are plotted in Figure 3 in terms of attenuation per wavelength ($\alpha\lambda$) versus f/P. The results show excellent agreement with the theory in Reference 5 near the resonance absorption peak. Although there are substantial deviations of some of the individual measurements of absorption in air over all the conditions tested, in general, the results tend to verify the validity of the prediction method in Reference 5 over a frequency range much lower than had been possible with previously published data.

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Table 2

Computer Program for Analysis of Resonance Absorption Data
(TYMSHARE SUPERFORTRAN)

```
C: THIS IS A DATA REDUCTION COMPUTER PROGRAM FOR THE
EXPERIMENT PERFORMED IN A SS CYLINDRICAL ACOUSTIC RESONATOR.
      REAL TEMP, PRES, HPMR, FMEA(23), T60(23),ETA,GAMA,DENG
      REAL DENS,VELS,DELT(23),F(23),VELG(23),D(23),DD(23)
      REAL DPR(23),RFP(23),VELGU(23)
      REAL ALPHA(23),ALPHAPW(23),ALPHAO(23),ALPHAOPW(23),ALPHAN(23)
      REAL LAMDA(23),RELAXO(23),RELAXN(23),ALPHANPW(23)
      REAL EALPHA(23),EALPHAPW(23),SRRFP(23),MALPHAO,MALPHAN
      C: TEMP IS THE TEMPERATURE IN DEGREE KELVIN
      C: PRES IS THE PRESSURE IN ATM
      C: HPMR IS THE HUMIDITY IN % MOLE RATIO
      C: FEMA IS THE MEASURED FREQUENCY IN HZ
      C: T60 IS THE REVERBERATION TIME IN SECONDS
      C: ETA IS THE VISCOSITY IN NT-SEC/MM
      C: GAMA IS THE SPECIFIC HEAT RATIO
      C: DENG IS THE DENSITY OF THE GAS IN KG/MMM
      C: DENS IS THE DENSITY OF THE STAINLESS STEEL IN KG/MMM
      C: VELS IS THE SOUND VELOCITY IN SS IN M/SEC
      C: DELT IS THE MEASURED RESONANCE HALFWIDTH
      OPEN(2,"MFREQT60")
10    READ(2,END=70)(FMEA(I),I=1,23)
      READ(2)(T60(I),I=1,23)
      DISPLAY (FMEA(I),T60(I),I=1,23)
      STRING S(50)
      ACCEPT "EXPERIMENT DESCRIPTION:",S
      ACCEPT "TEMPERATURE,DEGREE KELVIN=", TEMP
      ACCEPT "PRESSURE IN ATM=", PRES
      ACCEPT "VISCOSITY IN NT-SEC/MM=", ETA
      ACCEPT "HUMIDITY IN % MOLE RATIO=", HPMR
      ACCEPT "SPECIFIC HEAT RATIO=", GAMA
      ACCEPT "DENSITY OF GAS IN KG/MMM=", DENG
      ACCEPT "DENSITY OF STEEL IN KG/MMM=", DENS
      ACCEPT "SOUND VELOCITY IN SS IN M/SEC=", VELS
      ACCEPT "0 IS CALIBRATION AND 1 IS DATA IN AIR",K
      ACCEPT "NUMBER OF EVENTS=", N
      DO 20 I=1,N
      DELT(I)=2.199/T60(I)
      VELGU(I)=2*1.00*FMEA(I)/I
      F(1)=FMEA(I)
      VELG(1)=2*1.00*F(1)/I
      A=39.37/SQRT(GAMA)+41.37*((GAMA-1)/GAMA)*SQRT((9*GAM
          A-5)/4)
      DO 30 J=1,20
      D(J)=1.773E-3*VELG(J)*SQRT(ETA)*SQRT(F(J)/PRES)*A
      DD(J)=.637*(VELG(J)**2)*DENG/(VELS*DENS)
      VELG(J+1)=2*(F(J)+D(J)/2+DD(J)/2)/I
      F(J+1)=I*VELG(J+1)/2
      M=J
      IF(ABS(VELG(M+1)-VELG(M)) .LT. .5E-2) GO TO 50
      J=M
30    CONTINUE
```

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Table 2 (Continued)

```
50      50      VELG(I)=VELG(M+1)
51              F(I)=F(M+1)
52              LAMDA(I)=VELG(I)/F(I)
53              D(I)=1.77E-3*VELG(I)*SQRT(ETA)*A*SQRT(F(I)/PRES)
54              DD(I)=.637*(VELG(I)**2)*DENG/(VELS*DENS)
55              DPR(I)=(DELT(I)-(D(I)+DD(I)))/DELT(I)
56              EALPHA(I)=DPR(I)*DELT(I)*3.1415/VELG(I)
57              EALPHAPW(I)=EALPHA(I)*LAMDA(I)
58              RFP(I)=F(I)/PRES
59              SRRFP(I)=SQRT(RFP(I))
60              IF(K.NE.1)GO TO 20
61              FO=PRES*(24+4.41E4*HPMR*((.05+HPMR)/(.391+HPMR)))
62              NFACTOR=9+350*HPMR*EXP(-6.142*((TEMP/293)**.333-1))
63              FN=PRES*SQRT(TEMP/293)*NFACTOR
64              TFACO=2239.1/TEMP
65              TFACN=3352/TEMP
66              MALPHAO=.0376*(TFACO**2)*EXP(-TFACO)
67              MALPHAN=.140*(TFACN**2)*EXP(-TFACN)
68              RELAXO(I)=2*F(I)/(FO*(1+(F(I)/FO)**2))
69              RELAXN(I)=2*F(I)/(FN*(1+(F(I)/FN)**2))
70              ALPHAOPW(I)=MALPHAO*RELAXO(I)
71              ALPHANPW(I)=MALPHAN*RELAXN(I)
72              ALPHAO(I)=ALPHAOPW(I)/LAMDA(I)
73              ALPHAN(I)=ALPHANPW(I)/LAMDA(I)
74              ALPHA(I)=ALPHAO(I)+ALPHAN(I)
75              ALPHAPW(I)=ALPHA(I)*LAMDA(I)
76      20      CONTINUE
77              DISPLAY ""
78              DISPLAY S
79              IF(K.EQ.1)GO TO 65
80              DISPLAY""
81              DISPLAY"      F/P           SRRFP  FRAC DEVIATION      UNCOR VEL
                     COR VEL"
82              WRITE(1,60)(RFP(I),SRRFP(I),DPR(I),VELGU(I),VELG(I),I=1,N)
83      60      FORMAT(5(E10.3,3X))
84              DISPLAY""
85              GO TO 67
86      65      DISPLAY""
87              DISPLAY"   F/P      RATIO     EALPHA    EALPPW     ALPHA
                    ALPPW      ALOPW     ALNPW"
88              WRITE(1,66)(RFP(I),DPR(I),EALPHA(I),EALPHAPW(I),ALPHA(I),
                     ALPHAPW(I),ALPHAOPW(I),ALPHANPW(I),I=1,23)
89      66      FORMAT(8E9.3)
90              DISPLAY""
91      67      GO TO 10
92      70      CLOSE(2)
93              STOP
94              END
```

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Table 2a

Symbols and Abbreviations Used on Computer Printouts of Data

Abbreviation	Definition
T:	Temperature, degrees Kelvin
P	Pressure, atm
HPMR	Humidity, percent mole ratio
F	Frequency, Hertz
RATIO	[1 - surface attenuation (calculated)/total attenuation (measured)]
EALPHA	Experimentally measured attenuation, Nepers/m
EALPPW	Experimentally measured attenuation, Nepers/wavelength
ALPHA	Calculated attenuation due to oxygen and nitrogen molecular relaxation, nepers/m
ALPPW	Calculated attenuation per wavelength = (ALPHA) · (wavelength)
ALOPW	Calculated attenuation per wavelength due to oxygen relaxation
ALNPW	Calculated attenuation per wavelength due to nitrogen relaxation
SRRFP	Square root of f/p, $(Hz/atm)^{1/2}$
FRACTION DEVIATION	Same as Ratio
UNCOR VEL	Uncorrected speed of sound, m/sec
COR VEL	Corrected speed of sound, m/sec

Table 3

Calibration Data in Dry Argon at 1 atm

T = 291.9°K, P = 1 atm

Viscosity = 2.216×10^{-5} N -sec/m^2

Specific Heat Ratio = 1.664

Density = 1.67 kg/m^3

P/P	SRREF	FRAC DEVIATION	UNCOR VEL	COR VEL
.178E+03	.133E+02	--.962E--01	.315E+03	.316E+03
.344E+03	.185E+02	--.146E+00	.316E+03	.316E+03
.507E+03	.225E+02	--.140E+00	.315E+03	.317E+03
.670E+03	.259E+02	--.139E+00	.316E+03	.317E+03
.833E+03	.289E+02	--.136E+00	.316E+03	.317E+03
.995E+03	.315E+02	--.200E+00	.316E+03	.318E+03
.116E+04	.340E+02	--.181E+00	.315E+03	.318E+03
.132E+04	.363E+02	--.985E--01	.316E+03	.319E+03
.148E+04	.385E+02	--.215E+00	.316E+03	.319E+03
.164E+04	.405E+02	--.148E+00	.316E+03	.319E+03
.180E+04	.424E+02	--.235E+00	.316E+03	.320E+03
.196E+04	.443E+02	--.188E+00	.316E+03	.320E+03
.212E+04	.461E+02	--.173E+00	.316E+03	.321E+03
.228E+04	.478E+02	--.211E+00	.316E+03	.321E+03
.244E+04	.494E+02	--.245E+00	.316E+03	.321E+03
.260E+04	.510E+02	--.235E+00	.316E+03	.322E+03
.276E+04	.526E+02	--.222E+00	.316E+03	.322E+03
.292E+04	.541E+02	--.268E+00	.316E+03	.323E+03
.308E+04	.555E+02	--.262E+00	.316E+03	.323E+03
.324E+04	.570E+02	--.283E+00	.316E+03	.323E+03
.340E+04	.583E+02	--.290E+00	.316E+03	.324E+03
.356E+04	.597E+02	--.289E+00	.316E+03	.324E+03
.372E+04	.610E+02	--.253E+00	.316E+03	.324E+03

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Table 4

Calibration Data in Dry Argon at 9.5 atm

T = 291.6°K, P = 9.50 atm

Viscosity = 2.244×10^{-5} N - sec/m^2

Specific Heat Ratio = 1.642

Density = 15.9 kg/m^3

F/P	SRREF	FRAC DEVIATION	UNCOR VEL	COR VEL
.173E+02	.416E+01	--.473E--01	.316E+03	.317E+03
.342E+02	.585E+01	--.178E--01	.316E+03	.317E+03
.509E+02	.714E+01	--.267E--02	.315E+03	.317E+03
.677E+02	.823E+01	.195E--01	.316E+03	.317E+03
.847E+02	.921E+01	.244E--01	.316E+03	.317E+03
.102E+03	.101E+02	.101E--01	.316E+03	.317E+03
.118E+03	.109E+02	.135E--01	.316E+03	.317E+03
.135E+03	.116E+02	--.429E--01	.316E+03	.318E+03
.152E+03	.123E+02	--.142E--01	.316E+03	.318E+03
.169E+03	.130E+02	.218E--01	.316E+03	.318E+03
.185E+03	.136E+02	.391E--02	.316E+03	.318E+03
.202E+03	.142E+02	.344E--01	.316E+03	.318E+03
.219E+03	.148E+02	--.652E--02	.316E+03	.318E+03
.236E+03	.153E+02	.205E--01	.316E+03	.318E+03
.252E+03	.159E+02	.109E--01	.316E+03	.318E+03
.269E+03	.164E+02	.222E--01	.317E+03	.319E+03
.286E+03	.169E+02	.116E--01	.316E+03	.319E+03
.303E+03	.174E+02	.200E--01	.317E+03	.319E+03
.319E+03	.179E+02	.534E--02	.317E+03	.319E+03
.336E+03	.183E+02	.496E--02	.317E+03	.319E+03
.353E+03	.188E+02	.173E--02	.317E+03	.319E+03
.370E+03	.192E+02	--.159E--01	.317E+03	.319E+03
.386E+03	.197E+02	--.115E--01	.317E+03	.319E+03

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Table 5

Calibration Data in Dry Argon at 50.66 atm

T = 294.3°K, P = 50.7 atm

Viscosity = 2.319×10^{-5} N - sec/m^2

Specific Heat Ratio = 1.555

Density = 85.2 kg/m^3

P/P	SRREP	FRAC DEVIATION	UNCOR VEL	COR VEL
.328E+01	.181E+01	--.159E+00	.324E+03	.321E+03
.645E+01	.254E+01	--.870E--01	.322E+03	.321E+03
.965E+01	.311E+01	--.456E--01	.322E+03	.322E+03
.128E+02	.358E+01	--.327E--01	.322E+03	.322E+03
.160E+02	.400E+01	--.469E--02	.322E+03	.322E+03
.192E+02	.438E+01	--.779E--02	.322E+03	.322E+03
.224E+02	.473E+01	.139E--01	.322E+03	.322E+03
.256E+02	.506E+01	.213E--01	.322E+03	.322E+03
.288E+02	.536E+01	.252E--01	.322E+03	.322E+03
.319E+02	.565E+01	.482E--01	.322E+03	.322E+03
.351E+02	.593E+01	.532E--01	.322E+03	.322E+03
.383E+02	.619E+01	.814E--01	.322E+03	.322E+03
.415E+02	.644E+01	.567E--01	.322E+03	.322E+03
.447E+02	.668E+01	.101E+00	.322E+03	.322E+03
.478E+02	.692E+01	.782E--01	.322E+03	.322E+03
.510E+02	.714E+01	.712E--01	.322E+03	.322E+03
.542E+02	.736E+01	.815E--01	.322E+03	.322E+03
.574E+02	.757E+01	.813E--01	.321E+03	.322E+03
.606E+02	.778E+01	.116E+00	.322E+03	.322E+03
.637E+02	.798E+01	.130E+00	.322E+03	.323E+03
.669E+02	.818E+01	.105E+00	.322E+03	.323E+03
.701E+02	.837E+01	.848E--01	.321E+03	.323E+03
.732E+02	.856E+01	.785E--01	.321E+03	.323E+03

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Table 6

Calibration Data in Dry Argon at 98.8 atm

T = 294.3°K, P = 98.8 atm

Viscosity = 2.403×10^{-5} N - sec/m^2

Specific Heat Ratio = 1.555

Density = 171.1 kg/m^3

F/P	SRREP	FRAC DEVIATION	UNCOR VEL	COR VEL
.173E+01	.131E+01	--.454E+00	.332E+03	.332E+03
.341E+01	.185E+01	--.420E+00	.332E+03	.332E+03
.510E+01	.226E+01	--.321E+00	.332E+03	.332E+03
.679E+01	.260E+01	--.256E+00	.332E+03	.332E+03
.846E+01	.291E+01	.270E--01	.332E+03	.332E+03
.102E+02	.319E+01	--.183E+00	.332E+03	.332E+03
.118E+02	.344E+01	--.150E+00	.332E+03	.332E+03
.135E+02	.368E+01	--.117E+00	.332E+03	.332E+03
.152E+02	.390E+01	--.100E+00	.332E+03	.332E+03
.169E+02	.411E+01	--.762E--01	.332E+03	.332E+03
.186E+02	.431E+01	--.733E--01	.332E+03	.332E+03
.203E+02	.450E+01	.239E+00	.332E+03	.332E+03
.219E+02	.468E+01	--.536E--01	.332E+03	.333E+03
.236E+02	.486E+01	.556E--01	.332E+03	.333E+03
.253E+02	.503E+01	--.352E--01	.332E+03	.333E+03
.270E+02	.520E+01	--.218E--01	.332E+03	.333E+03
.287E+02	.535E+01	--.420E--02	.332E+03	.333E+03
.303E+02	.551E+01	.382E--01	.332E+03	.333E+03
.320E+02	.566E+01	.681E--01	.332E+03	.333E+03
.337E+02	.581E+01	.152E+00	.332E+03	.333E+03
.354E+02	.595E+01	.235E--01	.332E+03	.333E+03
.371E+02	.609E+01	.389E--01	.332E+03	.333E+03
.387E+02	.622E+01	.108E--01	.332E+03	.333E+03

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Table 7

Experimental Data in Air at 9.84 atm

T = 294.4°K, P = 9.84 atm, Humidity = 1.31 x 10^{-2} % Mole Ratio

Viscosity = 1.838 x 10^{-5} N - sec/m^2

Specific Heat Ratio = 1.392

Density of Air = 11.8 kg/m^3

E/P	RATIO	EALPHA	EALPPW	ALPHA	ALPPW	ALOPW	ALNPW
.181E+02	.395E-02	.206E-04	.412E-04	.264E-03	.528E-03	.333E-03	.195E-03
.357E+02	.982E-01	.786E-03	.786E-03	.747E-03	.747E-03	.614E-03	.133E-03
.533E+02	.145E+00	.149E-02	.995E-03	.138E-02	.923E-03	.828E-03	.950E-04
.708E+02	.123E+00	.141E-02	.707E-03	.208E-02	.104E-02	.968E-03	.733E-04
.883E+02	.185E+00	.255E-02	.102E-02	.276E-02	.111E-02	.105E-02	.594E-04
.106E+03	.178E+00	.266E-02	.888E-03	.339E-02	.113E-02	.108E-02	.499E-04
.123E+03	.225E+00	.385E-02	.110E-02	.393E-02	.112E-02	.108E-02	.430E-04
.141E+03	.213E+00	.384E-02	.959E-03	.439E-02	.110E-02	.106E-02	.378E-04
.158E+03	.198E+00	.371E-02	.823E-03	.477E-02	.106E-02	.103E-02	.336E-04
.176E+03	.249E+00	.526E-02	.105E-02	.509E-02	.102E-02	.989E-03	.303E-04
.194E+03	.195E+00	.401E-02	.729E-03	.537E-02	.976E-03	.948E-03	.276E-04
.211E+03	.211E+00	.463E-02	.772E-03	.559E-02	.932E-03	.907E-03	.253E-04
.229E+03	.211E+00	.482E-02	.741E-03	.578E-02	.890E-03	.866E-03	.234E-04
.246E+03	.210E+00	.495E-02	.707E-03	.594E-02	.849E-03	.828E-03	.218E-04
.264E+03	.218E+00	.539E-02	.719E-03	.608E-02	.811E-03	.791E-03	.203E-04
.281E+03	.185E+00	.454E-02	.567E-03	.620E-02	.775E-03	.756E-03	.191E-04
.299E+03	.217E+00	.568E-02	.668E-03	.630E-02	.741E-03	.723E-03	.179E-04
.316E+03	.212E+00	.567E-02	.630E-03	.639E-02	.710E-03	.693E-03	.170E-04
.333E+03	.210E+00	.578E-02	.609E-03	.646E-02	.680E-03	.664E-03	.161E-04
.351E+03	.195E+00	.538E-02	.538E-03	.653E-02	.653E-03	.638E-03	.153E-04
.368E+03	.197E+00	.558E-02	.531E-03	.659E-02	.628E-03	.613E-03	.145E-04
.386E+03	.195E+00	.564E-02	.513E-03	.664E-02	.604E-03	.590E-03	.139E-04
.403E+03	.183E+00	.533E-02	.464E-03	.669E-02	.581E-03	.568E-03	.133E-04

Table 8

Experimental Data in Air at 35.7 atm

T = 294.4°K, P = 35.7 atm, Humidity = 3.94 x 10^{-3} % Mole Ratio

Viscosity = 1.881 x 10^{-5} N - sec/m^2

Specific Heat Ratio = 1.37

Density of Air = 43.2 kg/m^3

F/P	RATIO	EALPHA	EALPPW	ALPHA	ALPPW	ALOPW	ALNPW
.498E+01	.480E-01	.151E-03	.301E-03	.194E-03	.387E-03	.223E-03	.164E-03
.986E+01	.717E-01	.336E-03	.336E-03	.634E-03	.634E-03	.428E-03	.206E-03
.147E+02	.146E+00	.887E-03	.591E-03	.120E-02	.801E-03	.609E-03	.192E-03
.196E+02	.236E+00	.181E-02	.906E-03	.185E-02	.927E-03	.760E-03	.167E-03
.245E+02	.278E+00	.249E-02	.998E-03	.256E-02	.102E-02	.879E-03	.144E-03
.294E+02	.302E+00	.305E-02	.102E-02	.327E-02	.109E-02	.965E-03	.126E-03
.342E+02	.337E+00	.383E-02	.109E-02	.397E-02	.114E-02	.102E-02	.111E-03
.391E+02	.362E+00	.456E-02	.114E-02	.464E-02	.116E-02	.106E-02	.991E-04
.439E+02	.380E+00	.517E-02	.115E-02	.525E-02	.117E-02	.108E-02	.893E-04
.488E+02	.399E+00	.589E-02	.118E-02	.581E-02	.116E-02	.108E-02	.812E-04
.536E+02	.411E+00	.646E-02	.118E-02	.632E-02	.115E-02	.107E-02	.744E-04
.582E+02	.425E+00	.712E-02	.119E-02	.678E-02	.113E-02	.106E-02	.689E-04
.634E+02	.422E+00	.732E-02	.113E-02	.717E-02	.110E-02	.104E-02	.636E-04
.682E+02	.430E+00	.781E-02	.112E-02	.753E-02	.108E-02	.102E-02	.592E-04
.731E+02	.430E+00	.810E-02	.108E-02	.785E-02	.105E-02	.991E-03	.554E-04
.779E+02	.444E+00	.881E-02	.110E-02	.813E-02	.102E-02	.964E-03	.521E-04
.828E+02	.442E+00	.901E-02	.106E-02	.838E-02	.986E-03	.937E-03	.492E-04
.876E+02	.438E+00	.910E-02	.101E-02	.860E-02	.956E-03	.909E-03	.465E-04
.925E+02	.451E+00	.983E-02	.103E-02	.880E-02	.926E-03	.882E-03	.441E-04
.973E+02	.434E+00	.942E-02	.942E-03	.898E-02	.898E-03	.856E-03	.420E-04
.102E+03	.438E+00	.978E-02	.932E-03	.913E-02	.870E-03	.830E-03	.400E-04
.107E+03	.432E+00	.978E-02	.889E-03	.928E-02	.843E-03	.805E-03	.382E-04
.112E+03	.444E+00	.105E-01	.909E-03	.941E-02	.818E-03	.781E-03	.366E-04

Table 9

Experimental Data in Air at 50.0 atm

T = 293.3°K, P = 50.0 atm, Humidity = 2.48 x 10^{-3} % Mole Ratio

Viscosity = 1.905 x 10^{-5} N - sec/m^2

Specific Heat Ratio = 1.36

Density of Air = 60.7 kg/m^3

P/P	RATIO	EALPHA	EALPPW	ALPHA	ALPPW	ALOPW	ALNPW
.231E+01	.147E+00	.423E-03	.846E-03	.125E-03	.250E-03	.149E-03	.101E-03
.458E+01	.230E-01	.946E-04	.946E-04	.460E-03	.460E-03	.291E-03	.169E-03
.683E+01	.976E-01	.495E-03	.330E-03	.939E-03	.626E-03	.424E-03	.202E-03
.909E+01	.204E+00	.130E-02	.648E-03	.152E-02	.758E-03	.548E-03	.210E-03
.113E+02	.370E+00	.321E-02	.129E-02	.216E-02	.863E-03	.659E-03	.204E-03
.136E+02	.314E+00	.267E-02	.889E-03	.285E-02	.950E-03	.756E-03	.193E-03
.158E+02	.345E+00	.326E-02	.930E-03	.357E-02	.102E-02	.840E-03	.180E-03
.181E+02	.397E+00	.428E-02	.107E-02	.431E-02	.108E-02	.909E-03	.168E-03
.203E+02	.427E+00	.508E-02	.113E-02	.504E-02	.112E-02	.965E-03	.156E-03
.225E+02	.450E+00	.581E-02	.116E-02	.577E-02	.115E-02	.101E-02	.145E-03
.248E+02	.476E+00	.670E-02	.122E-02	.648E-02	.118E-02	.104E-02	.135E-03
.270E+02	.499E+00	.759E-02	.126E-02	.715E-02	.119E-02	.107E-02	.126E-03
.292E+02	.512E+00	.828E-02	.127E-02	.780E-02	.120E-02	.108E-02	.118E-03
.315E+02	.513E+00	.856E-02	.122E-02	.841E-02	.120E-02	.109E-02	.111E-03
.337E+02	.519E+00	.900E-02	.120E-02	.899E-02	.120E-02	.109E-02	.105E-03
.359E+02	.526E+00	.950E-02	.119E-02	.952E-02	.119E-02	.109E-02	.991E-04
.382E+02	.533E+00	.101E-01	.118E-02	.100E-01	.118E-02	.109E-02	.939E-04
.404E+02	.535E+00	.104E-01	.115E-02	.105E-01	.117E-02	.108E-02	.893E-04
.426E+02	.551E+00	.113E-01	.119E-02	.109E-01	.115E-02	.106E-02	.850E-04
.448E+02	.550E+00	.115E-01	.115E-02	.113E-01	.113E-02	.105E-02	.812E-04
.470E+02	.539E+00	.112E-01	.107E-02	.117E-01	.111E-02	.104E-02	.776E-04
.492E+02	.546E+00	.118E-01	.107E-02	.120E-01	.109E-02	.102E-02	.744E-04
.514E+02	.538E+00	.116E-01	.101E-02	.124E-01	.107E-02	.100E-02	.714E-04

Table 10

Experimental Data in Air at 78.5 atm

T = 294.9°K, P = 78.5 atm, Humidity = 1.69 $\times 10^{-3}$ % Mole Ratio

Viscosity = 1.981 $\times 10^{-5}$ N - sec/m^2

Specific Heat Ratio = 1.34

Density of Air = 95.0 kg/m^3

F/P	RATIO	EALPHA	EALPPW	ALPHA	ALPPW	ALOPW	ALNPW
.355E+01	.610E-01	.181E-03	.363E-03	.165E-03	.329E-03	.193E-03	.136E-03
.701E+01	.140E+00	.660E-03	.660E-03	.565E-03	.565E-03	.373E-03	.193E-03
.105E+02	.232E+00	.143E-02	.951E-03	.110E-02	.733E-03	.536E-03	.196E-03
.140E+02	.323E+00	.254E-02	.127E-02	.172E-02	.859E-03	.678E-03	.181E-03
.174E+02	.376E+00	.351E-02	.140E-02	.239E-02	.957E-03	.794E-03	.162E-03
.209E+02	.377E+00	.381E-02	.127E-02	.309E-02	.103E-02	.887E-03	.144E-03
.244E+02	.408E+00	.464E-02	.133E-02	.380E-02	.109E-02	.956E-03	.129E-03
.278E+02	.432E+00	.543E-02	.136E-02	.449E-02	.112E-02	.100E-02	.116E-03
.313E+02	.440E+00	.590E-02	.131E-02	.514E-02	.114E-02	.104E-02	.106E-03
.347E+02	.457E+00	.660E-02	.132E-02	.575E-02	.115E-02	.105E-02	.965E-04
.382E+02	.461E+00	.702E-02	.128E-02	.631E-02	.115E-02	.106E-02	.887E-04
.416E+02	.497E+00	.843E-02	.141E-02	.683E-02	.114E-02	.106E-02	.821E-04
.451E+02	.473E+00	.793E-02	.122E-02	.730E-02	.112E-02	.105E-02	.763E-04
.486E+02	.474E+00	.823E-02	.118E-02	.772E-02	.110E-02	.103E-02	.712E-04
.520E+02	.475E+00	.853E-02	.114E-02	.810E-02	.108E-02	.101E-02	.668E-04
.555E+02	.473E+00	.871E-02	.109E-02	.845E-02	.106E-02	.993E-03	.629E-04
.589E+02	.477E+00	.908E-02	.107E-02	.875E-02	.103E-02	.971E-03	.594E-04
.623E+02	.478E+00	.934E-02	.104E-02	.903E-02	.100E-02	.948E-03	.562E-04
.658E+02	.478E+00	.961E-02	.101E-02	.928E-02	.977E-03	.924E-03	.534E-04
.692E+02	.470E+00	.951E-02	.951E-03	.951E-02	.951E-03	.900E-03	.508E-04
.727E+02	.475E+00	.992E-02	.945E-03	.971E-02	.925E-03	.877E-03	.485E-04
.761E+02	.467E+00	.980E-02	.891E-03	.990E-02	.900E-03	.854E-03	.463E-04
.796E+02	.462E+00	.980E-02	.852E-03	.101E-01	.876E-03	.831E-03	.444E-04

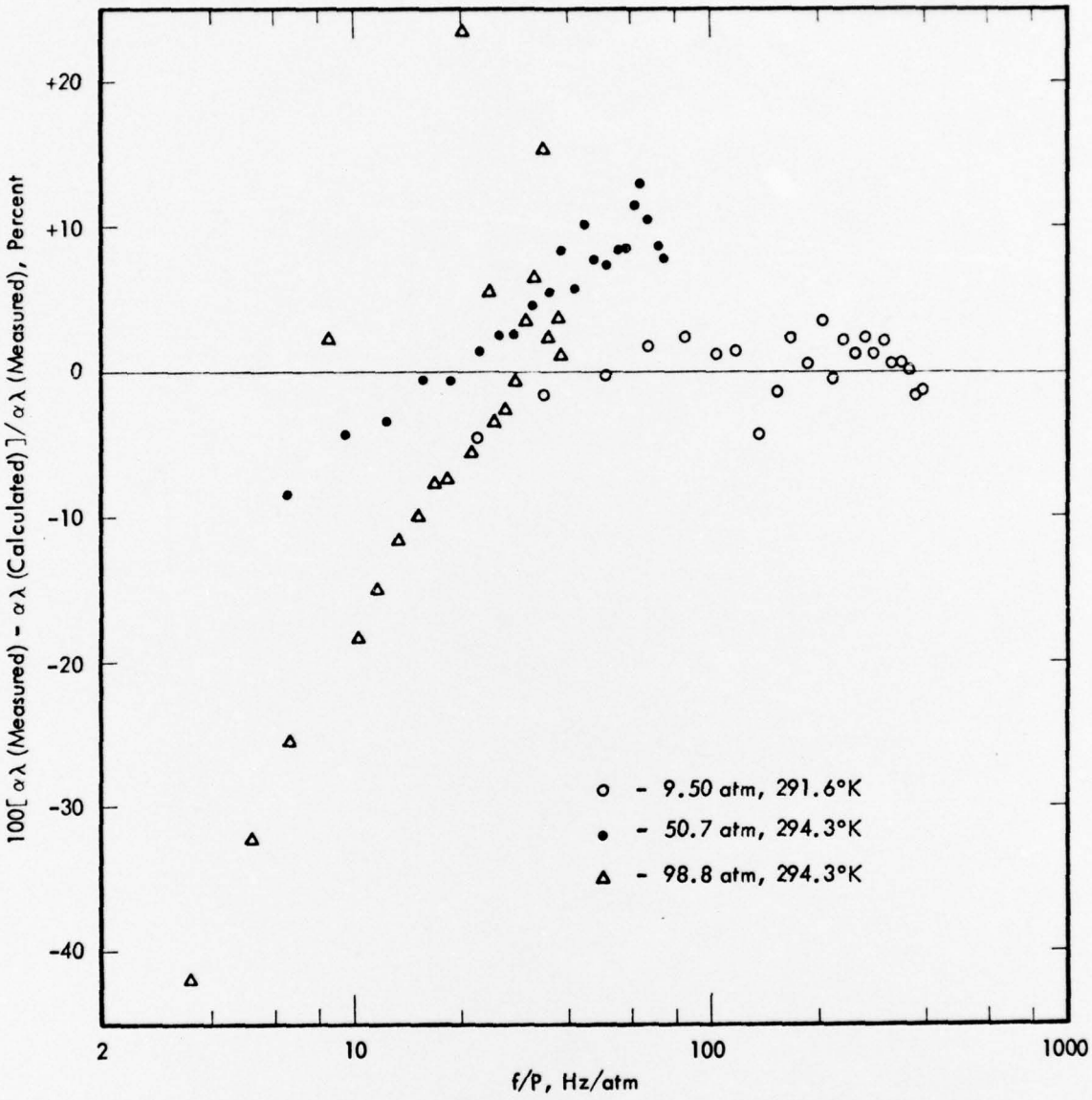

Figure 2. Difference Between Measured and Calculated Wall Losses for Calibration of Resonance Tube with Argon

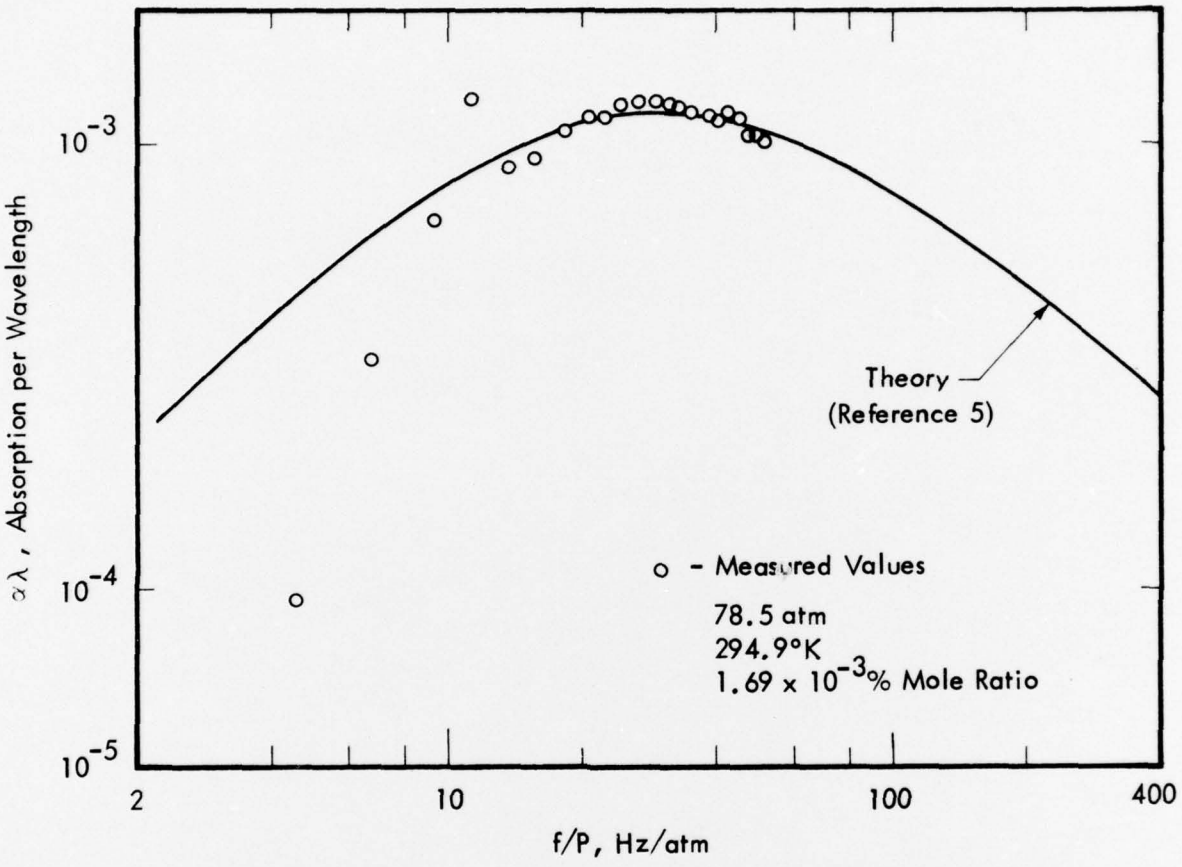

Figure 3. Absorption per Wavelength in Air at 78.5 atm

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APPENDIX A

PRESSURE SCALING IN ACOUSTIC ABSORPTION OF GASES

INTRODUCTION

Various competing acoustic absorption mechanisms in the gas contained in an acoustic resonator are considered in order to illustrate the frequency/pressure region in which the volumetric absorption is optimized. A general method for scaling tables of absorption loss at one atmospheric pressure to any other pressure is also defined. These concepts were applied to this investigation for examination of energy absorption at low frequencies.[1]

LIST OF SYMBOLS

f	Frequency, Hz
f_i	Molecular relaxation frequency, Hz
h	Absolute humidity, % mole ratio
h_r	Relative humidity, %
P	Pressure, *atm*
P_{sw}	Saturated water vapor pressure, atm
T	Temperature, ° Kelvin
z_g	Characteristic impedance of gas ($z_g = \rho_g c_g$), MKS rayls
α_{cl}, α_i, α_m, α_s	Absorption constants due to classical and rotational processes, direct mechanical radiation, molecular vibrational relaxation, and boundary layer interactions, respectively, N m^{-1}

PRESSURE SCALING CONCEPTS IN MEASUREMENT AND ANALYSIS

It is well-established that the effective frequency of an experimental measurement of sound absorption in any gas can be stated in terms of frequency per atmosphere or f/P (Hz/atm). This is due to the fact that the times of characteristic action

associated with the energy loss processes involved are inversely proportional to the ambient pressure. This can be seen clearly, for example, in the case of energy loss by molecular collision by observing that when the gas density is increased, the rate of collision will be increased proportionally. This results in a shorter length of time for the associated energy loss process to be completed.[2,3] The application of this f/P concept to an acoustic resonance apparatus is essential. For instance, f and P can be varied, separately or simultaneously, to cover such an f/P region within which the volumetric absorption will be enhanced and other absorption mechanisms suppressed. For measuring very low frequency molecular relaxation processes, a measurement can be taken first in the high pressure region giving optimum molecular absorption under all the experimental parameters considered, then the result converted to the ambient pressure by dividing the absorption value and the frequency by the pressure P. The concept can also be used to convert any tabular values of air absorption at 1 atmosphere to values for any other non-sea-level pressure (P) by simply finding the absorption at the same f/P value and multiplying the absorption magnitude at 1 atmosphere by the pressure P(atm). This concept is fully developed in the rest of this letter.

There are four mechanisms which cause the acoustic energy loss in a gas contained in a resonance apparatus.

- Thermal and viscous boundary layer losses at the gas/resonance chamber interface.
- Loss due to improved acoustic impedance match between the gas and the wall at high pressures.

- Molecular vibrational relaxation loss; and
- Classical and rotational relaxation losses

A. Boundary Layer Losses

It can be shown that, in the audio frequency range, the sound absorption constant due to the interaction between the gas and the wall in the boundary layer of a resonance apparatus, α_s, can be expressed as:[4]

$$\alpha_s = C_s (f/P)^{1/2} \qquad (1)$$

where C_s is a temperature-dependent coefficient. In a resonance apparatus, α_s often dominates the total energy loss at low pressures. However, it is obvious that the loss due to this process can be reduced by using small f/P values.

B. Direct Mechanical Radiation Losses (for high pressures) Through the Wall of the Resonance Apparatus

When pressure is increased inside the chamber, the characteristic impedance ($z_g = \rho_g c_g$) of the gas is also increased. This results in a more efficient acoustic impedance coupling between the gas and the resonator wall and, therefore, the mechanical radiation of the wall caused by the acoustic energy confined in the cavity is enhanced. It can be shown that the absorption constant due to this

mechanism when the acoustic impedance of the wall is much larger than that of the gas, is (neglecting any structural resonances of the tube):[5]

$$\alpha_i \simeq C_r z_g \tag{2}$$

where C_r is the proportionality coefficient. α_i provides a small, yet significant, correction to the data obtained from the resonance device. Since z_g is proportional to the gas density, α_i increases linearly with pressure for an ideal gas.

C. Molecular Vibrational Relaxation Loss

When considering a simple two-component parallel relaxing model for air, for example, the sound absorption constant , due to molecular vibrational relaxation loss, can be expressed as the sum of two terms:

$$\alpha_m = \alpha_{m,1} + \alpha_{m,2} \tag{3}$$

where each has the form

$$\alpha_{m,i} = C_i f_i \frac{(f/f_i)^2}{1 + (f/f_i)^2}, \quad i = 1,2$$

and C_1 and C_2 are proportionality coefficients which depend only on temperature for a given gas, and f_1 and f_2 are the molecular relaxation frequencies of the two gases, say oxygen and nitrogen.

As suggested above, both f_1 and f_2 are directly proportional to the atmospheric pressure for a constant temperature, and can be written:

$$f_1 \text{ or } f_2 \propto P \cdot F_1(h)$$

where $F_1(h)$ is a function of the absolute humidity h in percent mole ratio. This is given by:

$$h = P_{sw} \cdot h_r / P \qquad (4)$$

where P_{sw} is the saturated water vapor pressure at a specified temperature and h_r is the relative humidity in percent.

Several basic conclusions relative to pressure scaling of absorption measurements can be drawn from Eqs. 3 and 4.

- At constant temperature, P_{sw} is constant. This implies that, if the ratio h_r/P is maintained constant, then, from Eq. 4, the absolute humidity h is constant.
- When h is constant, f_1 and f_2 can be written as $C_1' P$ and $C_2' P$ respectively, where C_1' and C_2' are new coefficients for a given temperature.

- The molecular relaxation loss terms in Eq. 3 can be expressed as:

$$\alpha_m = P\left[C_1 C_1' \frac{(f/P)^2}{C_1^2 + (f/P)^2} + C_2 C_2' \frac{(f/P)^2}{C_2^2 + (f/P)^2}\right] \qquad (5)$$

$$= P \cdot F_2 (f/P, h, T)$$

where $F_2(f/P, h, T)$ is a complicated function of the ratio f/P, h and temperature, T. For either gas component at constant frequency, absolute humidity and temperature, the molecular absorption constant would vary with pressure as $P(P^2 + \text{constant})^{-1}$.

- Thus, for the same h and temperature, but for two different values of f and P, then if $f_1/P_1 = f_2/P_2$, then

$$\alpha_m(f_1/P_1) = (P_1/P_2)\, \alpha_m (f_2/P_2) \qquad (6)$$

It should be noted that for multiple relaxation processes in air, Eq. 6 is still true.[6,7] Therefore, low frequency molecular vibration absorption measurements can be obtained by performing an experiment with both frequency and pressure being scaled in such a way that f/P = constant providing the percent mole ratio h is also maintained the same, or in other words, the relative humidity h_r is properly scaled also so that the ratio h_r/P = constant. However, attention must always be given to the fact that h_r has an upper limit of 100. In the case of 1 Hz/1 atm = 100 Hz/100 atm, for example, if h_r/P is to be maintained constant, the relative humidity must be less than 1 percent at 1 atm.

D. Classical and Rotational Losses

Classical and rotational losses can be combined for frequencies in the audio range and expressed (ignoring without loss of generality, second order effects of humidity) as:

$$\alpha_{cl} = C_3 P (f/P)^2 = P \cdot F_3(f/P, T) \qquad (7)$$

where C_3 is a coefficient depending only on the temperature and $F_3(f/P, T)$ is a function of temperature and f/P. At constant temperature, α_{cl} increases linearly with P for a constant f/P, identical to the pressure scaling of α_m. Thus, for a constant temperature and absolute humidity, the total bulk absorption in the gas can be scaled for two different pressures P_1 and P_2 by the equation, where $f_1/P_1 = f_2/P_2$:

$$\frac{\alpha_m (f_1/P_1)}{P_1} + \frac{\alpha_{cl}(f_1/P_1)}{P_1} = \frac{\alpha_m (f_2/P_2)}{P_2} + \frac{\alpha_{cl}(f_2/P_2)}{P_2} \qquad (8)$$

CONCLUSION

It is always desirable and sometimes mandatory to reduce the boundary layer loss in a resonance apparatus to its minimum. According to Eq. 1, the lowest attainable (f/P) value in a resonance apparatus could be obtained at the highest achievable pressure and lowest available frequency, i.e., the fundamental resonance of the

apparatus. Maintaining f/P, h, and T constant, the high pressure will at the same time enhance the energy loss due to molecular relaxation processes, according to Eq. 5, further increasing the relative importance of α_m plus α_{cl} with respect to α_s. The correction due to mechanical radiation α_i can be applied to the difference between the total loss and that due to boundary layer resulting in a net loss due to molecular relaxation and classical absorption processes in a gas. As an example, these general trends in the magnitudes of the boundary and bulk losses in a resonance apparatus as a function of pressure are indicated in Figure 1 for an oxygen gas at $T = 20° C$, $f = 3500$ Hz and an absolute humidity of 10^{-2} percent mole ratio. The resonance tube considered has a radius of .025 m and a length of 1.0 m. The lines are all terminated at 230 atm for this case since the relative humidity would exceed 100% at higher pressures. The classical and rotational losses are several orders of magnitude lower than those due to the other three mechanisms in this example. It is clear that within the available experimental pressure region, the absorption originating from any one of these three mechanisms can be dominant. The operating pressure region yielding optimum molecular absorption is shown in Figure 1 as lying between 30 to 200 atm for the particular example. The actual position of these trend lines depends, of course, on the geometry of the apparatus, on the gas used, on the frequency, on the moisture content, and on the gas temperature. An "optimum" range for measurement of bulk losses is suggested, however, by the shaded area. This optimization approach was utilized in this laboratory measurement of absorption in air and argon.

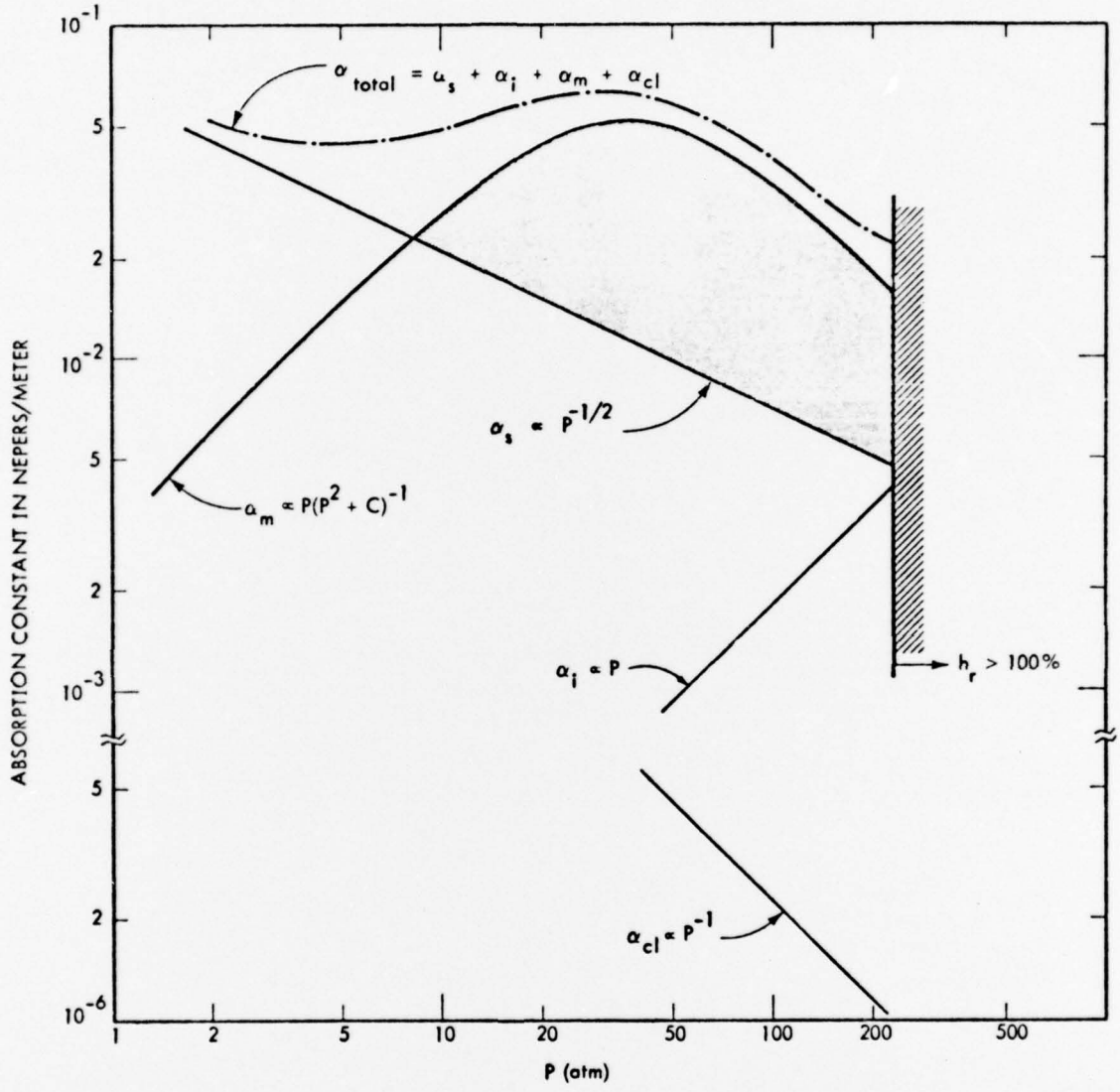

Figure 1. Trends in Surface (α_s), Impedance (α_i) and Volumetric Absorption Constants (α_m and α_{cl}) as a Function of Pressure in a Cylindrical Acoustic Resonance Apparatus for an Oxygen Gas Assuming a Constant Frequency, Temperature and Absolute Humidity. The Optimum Region for Volumetric Absorption Measurements is Suggested by the Shaded Area. The Resonance Tube Considered in this Example has a Radius of .025 m and a Length of 1.0 m. f = 3500 Hz, T = 20°C and h = 10^{-2} Percent Water Mole Ratio.

In conclusion, it is important to note that the acoustic resonance apparatus has its maximum usage only at low f/P values, if the molecular relaxation loss is the quantity to be measured. However, other thermodynamically important parameters, such as the coefficient of viscosity, the ratio of specific heats, the coefficient of thermal conductivity, etc., can be measured at high f/P values. For measuring very low frequency molecular relaxation processes, a measurement can be taken first in the low f/P region of the resonance apparatus, then the result converted to the ambient pressure and equivalent frequency by dividing the absorption value and the frequency by the pressure P. Furthermore, Eq. 8 can be used to convert any tabular values of air absorption at 1 atmosphere to values for any other non-sea-level pressure (P) by simply finding the absorption at the same f/P value and multiplying the absorption magnitude at 1 atmosphere by the pressure P(atm). These pressure scaling relationships are strictly valid only when the gas can be considered ideal (i.e., below about 2 atmospheres). However, the general trend in boundary and bulk losses versus pressure in a resonance tube apparatus will still apply.

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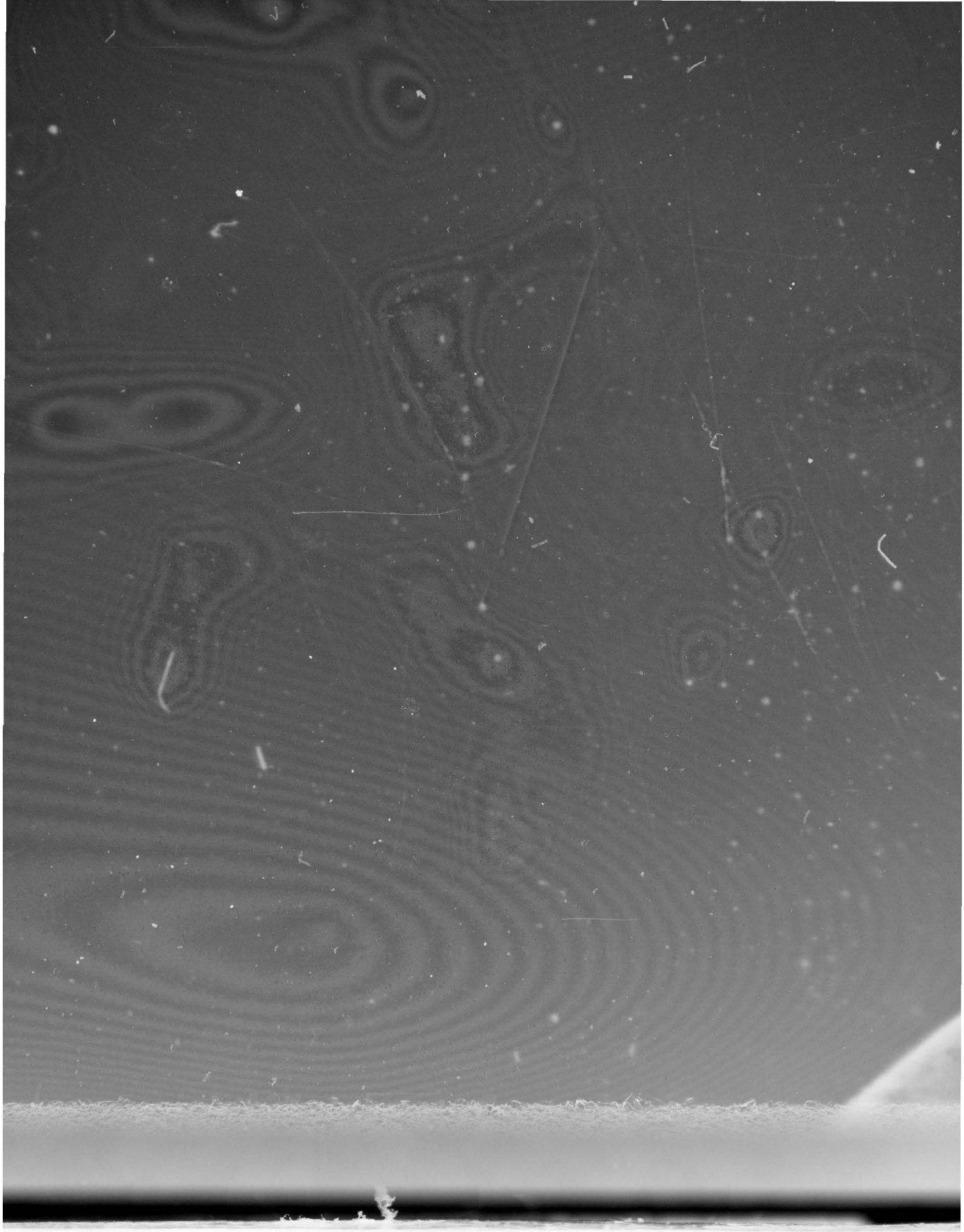
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